

NASA's Sentinels Monitoring Weather and Climate: Past, Present, and Future

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Weatherwise is probably the most popular newstand magazine focusing on the subject of weather. It is published six times per year and includes features on weather, climate, and technology. This article (to appear in the January/February Issue) provides a comprehensive review of NASA's past, present, and future contributions in satellite remote sensing for weather and climate processes. The article spans the historical strides of the TIROS program through the scientific and technological innovation of Earth Observer-3 and Global Precipitation Measurement (GPM). It is one of the most thorough reviews of NASA's weather and climate satellite efforts to appear in the popular literature.

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A few years ago, someone told me the story of a scientist who was in the desert seeking evidence of the existence of a very large, prehistoric dinosaur. One day, while standing in what seemed to be a large sink hole, the scientist uttered in frustration, "I see no evidence of this dinosaur anywhere." However, his assistant contacted him from a plane flying above to inform him that he was standing inside a huge footprint. This little anecdotal story illustrates the importance of perspective. Many weather and climate processes are naturally large in space and/or time and require a broader perspective for observation and prediction than traditional ground-based observations can provide. For almost 50 years, satellites have proven themselves as the most viable way to see the Earth's ever-changing atmospheric processes in motion. Jules Verne in 1860 wrote about "Lunonauts" observing cloud systems. Today, could you imagine a hurricane season without the watchful eye of the Geostationary Operational Environmental Satellite (GOES) weather satellites to warn of the approach of a storm like Hurricane Andrew or Floyd? Thankfully, when the Television Infrared Observation Satellite (TIROS-I) was launched on April 1st, 1960, it was no April Fool's joke that this camera orbiting the Earth could send back pictures of cloud systems, hurricanes, sea ice, and land masses. **(Figure 1)**

The atmosphere interacts with solar radiation much like a venetian blind—selectively absorbing and reflecting certain wavelengths of solar energy while allowing others to pass through. Engineers design satellite remote sensors to be particularly sensitive to those wavelengths that can be reflected or emitted back up through the atmosphere to space, thus enabling them to make their measurements. Earth-orbiting remote sensors provide the best means of collecting the data scientists need because they can measure things on scales of time and space that otherwise would not be possible. Moreover, satellite sensors not only observe wavelengths of visible light, they also precisely measure wavelengths of radiant energy that our eyes cannot see, such as microwaves, ultraviolet rays, or infrared light. **(Figure 2)** If scientists know how certain objects (like cirrus clouds or windblown dust) typically absorb, reflect, and emit particular wavelengths of radiant energy, then by using satellite sensors to precisely measure those specific bands of the electromagnetic spectrum, scientists can learn a lot about the Earth's atmosphere and surface.

Satellites have evolved from simply "staring at Earth's weather" to developing technologies that exploit the electromagnetic spectrum (think back to your physics class) to fully understand, link, and predict changes in the Earth system. Here, we explore how the National Aeronautics and Space Administration (NASA) and its international and domestic partners are using the Earth Observing System, other research satellites, and operational satellites like GOES to address fundamental questions about weather and climate. Such understanding is not simply scientific curiosity, it is vital part of the "toolbox" needed to provide new Earth observations, better initial conditions for

computer forecast models, or improved understanding of weather/climate processes. All of the previous advances enable useful knowledge for society.

Satellites are used in testing and developing ways to improve global weather forecasting and to understand how climate is changing. Satellites are vital in predicting where and when tropical storms, hurricanes, floods, cyclones, forest fires and even El Nino may strike. Knowing this information in advance allows time to prepare for these events and avoid disaster. Advanced weather and climate information helps farmers decide when to plant or harvest their crops or prevent their destruction by hail or snow. Satellite information may warn citrus growers of frost and sugarcane farmers of rain that may affect harvesting and growth. An accurate weather forecast also can allow engineers to schedule the best time for construction of large-scale projects such as bridges, highways, and dams.

NASA and Weather Satellites: Brief History

The creation of NASA on October 1st, 1958 was a fundamental step toward the advent of the field of satellite meteorology. Following the formation of NASA, a series of milestones in satellite meteorology occurred. In 1959, the U.S. Army launched the first satellite meteorological instrument called Vanguard 2. However, orbit problems rendered its data useless. Explorer 6 also launched in 1959 with a meteorological package including an imaging system and an innovative radiometer system developed by Verner Suomi and colleagues at the University of Wisconsin. It went into a highly elliptical orbit and its data was essentially useless as well. However, it did provide the first Earth photo. TIROS was the first series of satellites dedicated to meteorological processes. TIROS-1 carried television cameras to photograph the Earth's cloud cover and demonstrate the value of using spacecraft for meteorological research and weather forecasting.

Nimbus, a second-generation meteorological satellite, named for a cloud formation, was larger and more complex than the TIROS satellites. NASA initiated the Nimbus program to test a global meteorological satellite system. Nimbus 1 was launched in 1964 and carried two television cameras and two infrared cameras. Although Nimbus 1 had only about a one-month life-span, the satellite tracked the storm pattern of Hurricane Cleo helping prevent severe damage. Nimbus 7 operated from 1978 through 1993. This satellite carried a Total Ozone Mapping Spectrometer (TOMS) that played a major role in the study of both global ozone and the "ozone hole" over the Antarctic. NASA and other agencies pioneered several systems from the TIROS era to the GOES/POES era.

GOES and the Polar Orbiting Environmental Satellite (POES) series were built for the National Oceanic and Atmospheric Administration (NOAA) under technical guidance and management by NASA. Over nearly two decades, GOES has evolved into a world-class observing weather observing system (**Figure 3**). GOES satellites provide the now-familiar weather pictures seen on newscasts worldwide. Each satellite in the series carries two major instruments, an imager and a sounder, which acquire high-resolution visible and infrared data, as well as temperature and moisture profiles of the atmosphere. Like GOES, the POES series continues to provide high resolution imaging and sounding of the atmosphere for assessing the weather and providing vital input for weather forecast models in the form of atmospheric profiles of temperature and moisture. In 2002, NOAA-17 (M) was launched into orbit on a mission to provide imaging and sounding capabilities and operate over the next 10 years. NASA and its partners in the Department of Defense and NOAA are currently transitioning the polar-orbiting weather satellite program of all three agencies into one program called the Next-Generation POES. An interagency office called the Integrated Program Office (IPO) is coordinating and managing this effort.

If one looks at a broad historical evolution of Earth Science, which includes weather and climate, there are four distinct eras. The 1960s to 1980s represented a time for *exploring possibilities*. During this era, the birth and early development of satellite remote sensing was occurring with TIROS, Nimbus, and others. In other words, technology demonstration and feasibility was the driver. The decade 1990 to 2000 represented a time for *surveying the Earth System*. During this period, the concept of all of the Earth's systems (e.g. weather, climate, land, ocean, and ice) being inter-related emerged. The objective was to provide observations that document how the Earth is changing and what are the consequences of these changes. For example, if climate change is occurring, how will weather patterns, hurricane intensity, or flood frequency change. The current period from 2000 to 2020 is marked by a shift to a *focus on national needs*. This "science serving society" focus will answer science questions that have an impact on national/international societal and economic policies. For example, how can global precipitation measurements from space be utilized to improve freshwater resource management or agriculture? The period of 2020 and beyond will be marked by *broad use of the view from space* by making space information available to users in a timely and affordable manner. For example, this period might allow a weekend gardener to access NASA satellite rainfall data for the location of his vegetable garden.

NASA Satellites Monitoring the Atmosphere

NASA's mission statement is "To understand and protect our home planet, To explore the universe and search for life, To inspire the next generation of explorers...as only NASA can." The Earth Observing System (EOS) is the centerpiece of NASA's Earth Science Enterprise (ESE) and its effort to address the first statement in that vision. EOS is composed of a series of satellites, a science component, and a data system supporting a coordinated series of low Earth orbit satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. EOS will enable an improved understanding of the Earth as an integrated system. This is particularly relevant to weather and climate because we are increasingly aware of how weather is impacted by the ocean (El Nino/La Nina), land processes (land-use change), and atmospheric pollutants. NASA has established a set of expected outcomes from its Earth Science research strategy related to improved 3-to-7 weather forecasts, hurricane prediction, and climate variability and change. It is interesting to explore some of the current and future satellite systems (research and operational) that NASA is associates with, independently or in partnership, that will help enable such improvements.

On December 19th, 1999, the first of several EOS spacecraft, Terra (or "land,") was launched into a polar orbit. Its orbit is synchronous with the Sun, with the satellite tracking south across the equator at approximately 10:30 am local time. It was formerly known as EOS-AM. It's sister spacecraft, Aqua (or "water,") was launched on May 4th, 2002 and is in a similar orbit but crosses the equator at 1:30 pm and is formerly known as "EOS-PM." **(Figure 4)** Both satellites emphasize NASA's commitment to international partnerships with instruments provided by Japan, Canada, and Brazil among others. Vince Salomonson of NASA's Goddard Space Flight Center in Greenbelt, Maryland noted that the Terra and Aqua spacecraft allow us to observe rapidly changing processes like clouds and water vapor. Understanding the movement of water in various forms through the atmosphere is essential for climate and local weather modeling. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard both Terra and Aqua will augment scientists' ability to track wind and clouds in the polar regions where current weather satellites can't "see" due to orbit track or inadequate sensor bands, helping meteorologists to better monitor and predict global weather patterns. Also, Terra's MODIS instrument routinely provides daily global and local measurements of

albedo, or the total amount of light reflected from Earth's surface or clouds back to space. Some refer to albedo as the "Earthshine" (**Figure 5**). These precise data may allow scientists to better understand and predict how various surface features absorb and reflect solar radiation, which influence both short-term weather patterns and longer-term climate trends. Recent observations from NASA's Terra satellite, with improved sensitivity to detect cirrus clouds, suggest that cirrus are present more than expected both temporally and spatially across the planet. Cirrus may act to warm or cool the planet and the tendency toward warming or cooling depends on the extent, duration, thickness, and location of the clouds. Essentially, you might think of cirrus as a type of blanket. Clouds, particularly cirrus, are major sources of uncertainty in today's global climate models. (**Figure 6**)

Another set of instruments on Aqua, the Atmospheric Infrared Sounder spectrometer and its two companion instruments--the Advanced Microwave Sounding Unit and the Humidity Sounder for Brazil--are exceeding the expectations of the world meteorological community. These three sounding instruments capture a continuous, detailed picture of Earth's atmospheric temperature and moisture structure from the ground to top of the troposphere and should lead to increased accuracy of short-term weather predictions, improved tracking of severe weather events like hurricanes, and advances in climate research. (**Figure 7**) NASA's Claire Parkinson, Aqua project scientist, said the impact on world commerce from improved weather and climate may be enormous because of these new orbiting "thermometers" and "hygrometers."

Hurricanes continue to inspire, puzzle, and destroy, yet remain one of the least predictable phenomena in nature. To improve understanding, monitoring, and prediction of these amazing storms, NASA has launched three satellites that will help. The Tropical Rainfall Measuring Mission (TRMM), QuikSCAT, and Aqua satellites each look at different factors of tropical cyclones to help generate better diagnosis and forecasts. TRMM focuses on the intensity of tropical rainfall, which is indicative of whether a cyclone is weakening or strengthening. Its revolutionary precipitation radar can actually peer inside the hurricane to identify rapidly developing thunderstorms in the eyewall, which may signal intensification (**Figure 8**). A typical infrared (IR) image of a satellite can only sense the hurricane cloud tops. Using an analogy, TRMM allows us to "look under the hood at the hurricane engine" whereas previous IR capabilities allow us to only feel the heat on the hood of the car. TRMM can also measure the temperature of the ocean through clouds, unlike infrared techniques, which require cloud-free conditions. As the figure shows (**Figure 9**), the additional information on sea-surface temperature is critical since hurricanes require warm water for development. "NASA's TRMM satellite has been very valuable in determining hurricane or tropical cyclone intensity and in improving hurricane track forecasting through the use of rainfall data into hurricane forecast computer models," said Bob Adler, TRMM Project Scientist at NASA's Goddard Space. TRMM data have been combined with data from other satellites to detect heavy rain events and the associated flood potential due to tropical cyclones in areas where there is limited ground based information.

The SeaWinds instrument on NASA's Quick Scatterometer spacecraft, also known as QuikSCAT, is a specialized microwave radar that measures both the speed and direction of winds near the ocean surface. It is being used by many marine weather prediction centers to improve monitoring and forecasting of tropical cyclones. In January 2002, the United States and Europe incorporated wind speed and direction data from QuikSCAT into their operational global weather analysis and forecast systems. Significant improvement has been demonstrated. (**Figure 10**) The sounding instruments aboard Aqua will also contribute to hurricane forecasting. NASA and its partners hope these data will lead to improved weather forecasts and improved determination of cyclone intensity,

location and tracks and the severe weather associated with storms. "The improved data from Aqua will not make weather forecasting perfect, but should make it better," said Claire Parkinson, Aqua Project Scientist at NASA Goddard.

NASA researchers, working with hurricane forecasters from the National Hurricane Center (NHC) hope that the data generated from these research satellites will improve hurricane predictions. NHC, part of the NOAA, NASA, and other federal agencies work together to provide the public with the best information possible. The NHC uses several computer models to help forecast and track the intensity of tropical cyclones. Each computer model includes air temperature and pressure, sea surface temperature, wind speed and humidity as recorded from hurricane hunter aircraft that fly above tropical cyclones and drop sensors into them to get this data. The NHC also verifies storm locations with NOAA's GOES series of satellites.

The TRMM satellite's contribution to hurricane research is an unanticipated benefit, which is very typical of many of NASA's satellite missions. TRMM was launched on Thanksgiving day in 1997 as a 3-year mission and even today, is continuing to collect a variety of measurements used to answer an array of key climate and weather questions related to Earth's water cycle. One of the great achievements of the TRMM program is the breadth of its science, and the diversity of societal applications. According to Jeff Halverson, TRMM Outreach Scientist, "TRMM meteorologists have discovered how microscopic dust particles interact with clouds to hinder the formation of rain. We have a better understanding of how rainfall and energy are distributed around the core of deadly hurricanes, and how clusters of rain clouds migrate across the Pacific Ocean during an El Nino. **(Figure 11)** Rainfall is inherently fickle across the tropics, and societies suffer through unrelenting cycles of drought and flood. TRMM is allowing us to measure these extreme variations with better accuracy than ever before." Answering questions about precipitation and the water cycle that we learned about in grade school is particularly important because availability of freshwater moving around the earth is vital. However, of all the water contained on Earth, roughly 1% is freshwater available for use by humans. TRMM carries the world's first space-based precipitation radar along with a lightning sensor and other visible, infrared, and microwave instruments. This unique package has revolutionized the way we view storm systems and rainfall by providing "Cat-Scan capabilities" through clouds. Rainfall information from TRMM is also starting to show positive results on error reduction when fed into experimental and operational climate, weather, and hurricane forecast models. Even the National Hurricane Center and the military routinely utilize TRMM data for its operational hurricane monitoring activities. A recent article in the November/December issue of *Weatherwise* highlights accomplishments of TRMM **(Figure 12)**.

TOPEX/Poseidon, a joint NASA-French Space Agency mission to study ocean circulation and its effect on climate, turned 10 years old in 2002 and still continues to be a silent sentinel watching over the world's oceans, looking for signs of the mysterious El Nino and La Nina phenomena whose cantankerous dispositions wreak havoc on our weather. "TOPEX/Poseidon data help forecast short-term changes in weather and longer-term climate patterns," said oceanographer William Patzert of NASA's Jet Propulsion Laboratory in California. "Ocean currents flow around highs and lows of oceanic pressure, distributing the Sun's heat across the globe and releasing it back into the atmosphere as water vapor, which is returned to the oceans and land as rain or snow. Understanding the oceans' behavior is the key to forecasting climate change." **(Figure 13)**

In 2002, NASA also launched the Gravity Recovery and Climate Experiment (GRACE) and JASON missions to more precisely track changes in the Earth's gravity field. It is believed that such changes may be caused by climate change, but could also be part of

normal long-period climatic variation. NASA also continues its routine monitoring of atmospheric ozone and its link to climate change. Since 1978, TOMS has been monitoring ozone and was instrumental in discovering the ozone hole. In 2000, TOMS data revealed the largest Antarctic Ozone hole on record. The hole was three times the size of the United States (**Figure 14**). It is well known that the ozone hole can exhibit variability, therefore, continued observations are critical. In 2001, NASA scientist also demonstrated TOMS' ability to track pollution plumes of smoke and smog. The chemical-aerosol processes in the stratosphere and troposphere are emerging science issues in weather, climate, and Earth Science research and applications. (**Figure 15**).

Because Earth is a system, the land and atmosphere can not be easily separated from the weather and climate processes in the atmosphere. NASA's current satellite fleet includes or will include satellites that focus on land (Landsat 7 and Earth Observer 1) and ocean (TOPEX Poseidon, SeaWiFS), both of which are ultimately linked to the atmosphere through processes like El Nino, La Nina, land use/land change, biomass burning, and the various Earth System cycles (water, carbon, etc.). To illustrate the power of these systems, it is fascinating to observe the high-resolution capabilities of Earth Observer 1 as it reveals the devastating path of deadly tornadoes that ripped through La Plata, Maryland in 2002. (**Figure 16**).

Where are We Headed

It is impossible within this space to capture the entire scope of how satellites in NASA's Earth Science Enterprise are contributing to our understanding and predictive capabilities in weather and science. But it is exciting to realize that NASA, in cooperation with partners in the U.S. and abroad, are on the verge of launching future satellites that will continue to advance our capabilities. (**Figure 17**)

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), while demonstrating new technology, will provide high resolution temperature, moisture, and wind data to initialize weather forecast models. Since forecast models depend on accurate "first guesses" of what is currently happening in the atmosphere at all times, GIFTS offer real potential to significantly improve weather forecasts.

The Global Precipitation Measurement (GPM) mission will use a constellation of 8-10 satellites to provide the most accurate global measurement of precipitation ever. Such information is needed to advance climate prediction, weather forecasting capabilities, and flood and freshwater resource assessment. GPM also represents a broad international partnership between the U.S., Japan, and others.

ICESat (Ice, Cloud, and Land Elevation Satellite) is the benchmark EOS mission for the measuring of ice sheet mass balance, cloud and aerosol heights and optical densities, height of vegetation, and land topography.

CloudSat will fill a significant gap in the existing and planned Earth observation missions by measuring the vertical profile of clouds using a space-based cloud radar. CloudSat information will be enhanced by formation flying with the Aqua and a future mission, Aura, which is focused on measuring chemical constituents like Ozone in the atmosphere. (**Figure 18**)

The Orbiting Carbon Observatory, a NASA Pathfinder mission that partners with industry and academia, will generate knowledge needed to improve projections of future carbon dioxide levels within Earth's atmosphere. Increasing carbon dioxide (CO₂) concentrations have raised concerns about global warming. Even though the biosphere

and oceans are currently absorbing about half of the CO₂ generated by human activities, the nature and geographic distribution of these CO₂ sinks are too poorly understood to predict their response to future anthropogenic CO₂ emissions and other system changes.

In summary, our scientist at the beginning of this article had a narrow view on his science problem, which limited his grasp on the problem. NASA's Earth Science Enterprise and satellites (along with its partners, scientists, and resources) are significantly broadening the view of meteorologists, climatologists, and those who use weather/climate information routinely. As Earth changes, it is critical that we understand the forcing mechanisms of the changes (human and/or natural), the consequences of the changes, and how to make better predictions of the change. It is not unreasonable for one to surmise that we are entering an era of unprecedented observation and prediction of our day-to-day weather and longer term climate, which ultimately benefits every farmer, planner, policymaker, and citizen of planet Earth. **(Figure 19).**

For more information on NASA's Earth Science Enterprise, the following websites are excellent resources:

<http://earth.nasa.gov>

<http://earthobservatory.nasa.gov>

<http://visibleearth.nasa.gov>

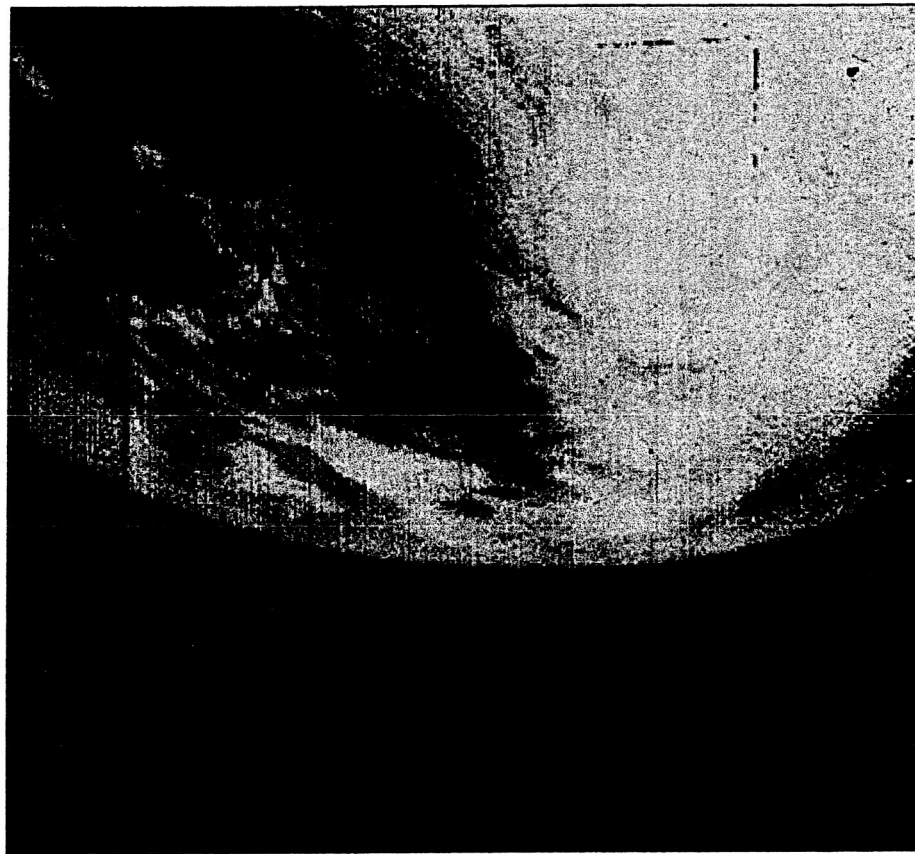


Fig. 1-TIROS-1 carried television cameras to photograph the Earth's cloud cover and demonstrate the value of using spacecraft for meteorological research and weather forecasting. The image above is the first image of the Earth from TIROS-1. (Image courtesy of the NASA's Earth Observatory).

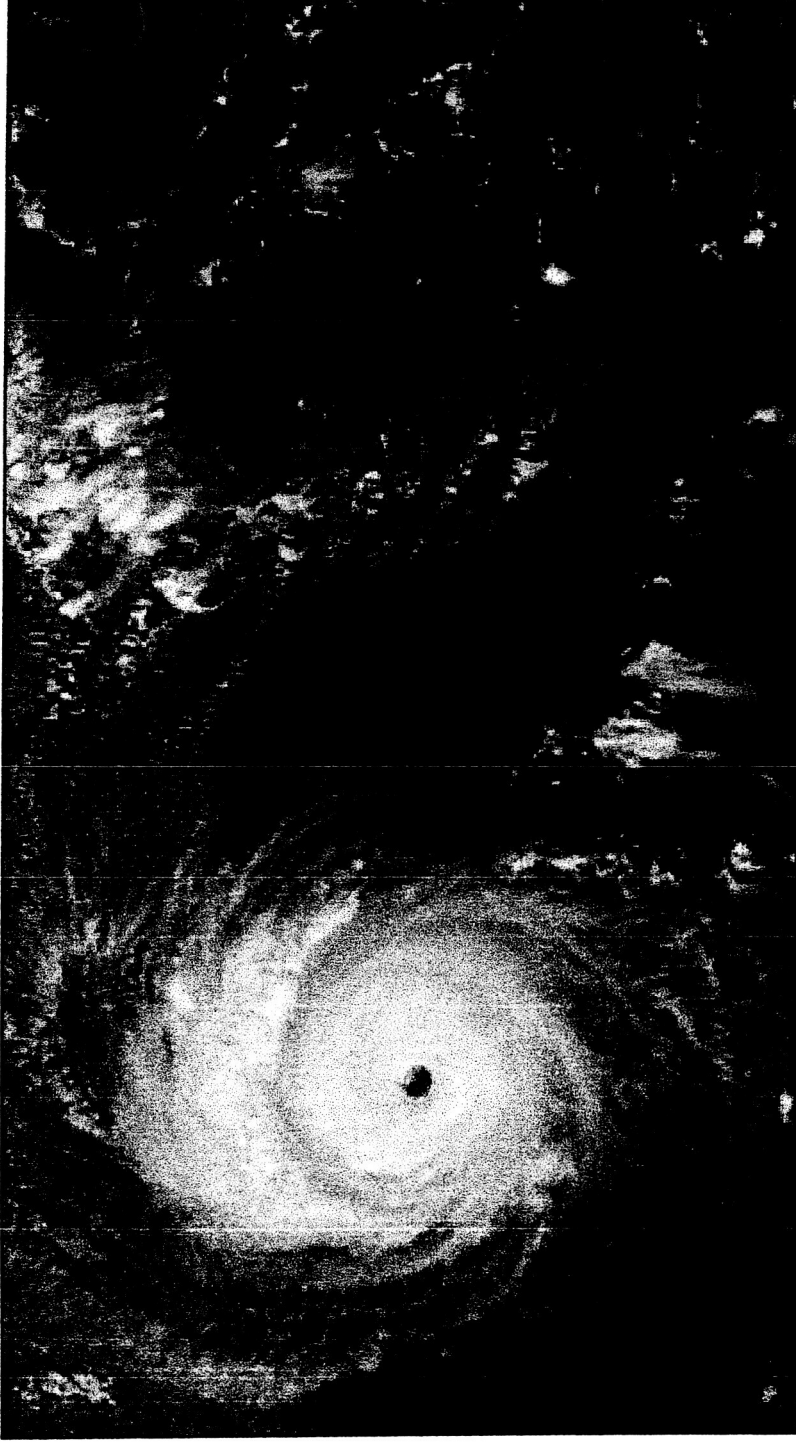


Fig. 3-Hurricane Andrew Heads for Louisiana. This is an overhead view of Hurricane Andrew as it approaches Louisiana on August 25, 1992 at 20:20 UT. The cloud data are from GOES-7 (Geostationary Operational Environmental Satellite), while the vegetation is derived from AVHRR (Advanced Very High Resolution Radiometers). During the previous day, Hurricane Andrew left a swath of devastation in southern Florida. CREDIT: NOAA and the NASA Goddard Laboratory for Atmospheres.

Terra



Aqua

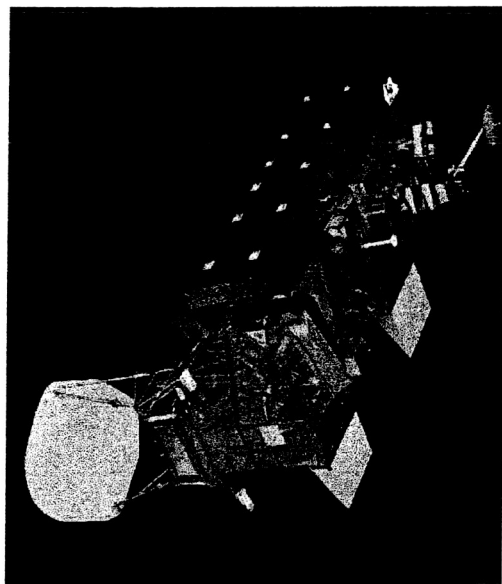


Fig. 4-Terra and Aqua Observatories, flagship spacecraft of NASA's Earth Observation System. Terra was launched December 19th, 1999, and Aqua was launched May 4th, 2002.

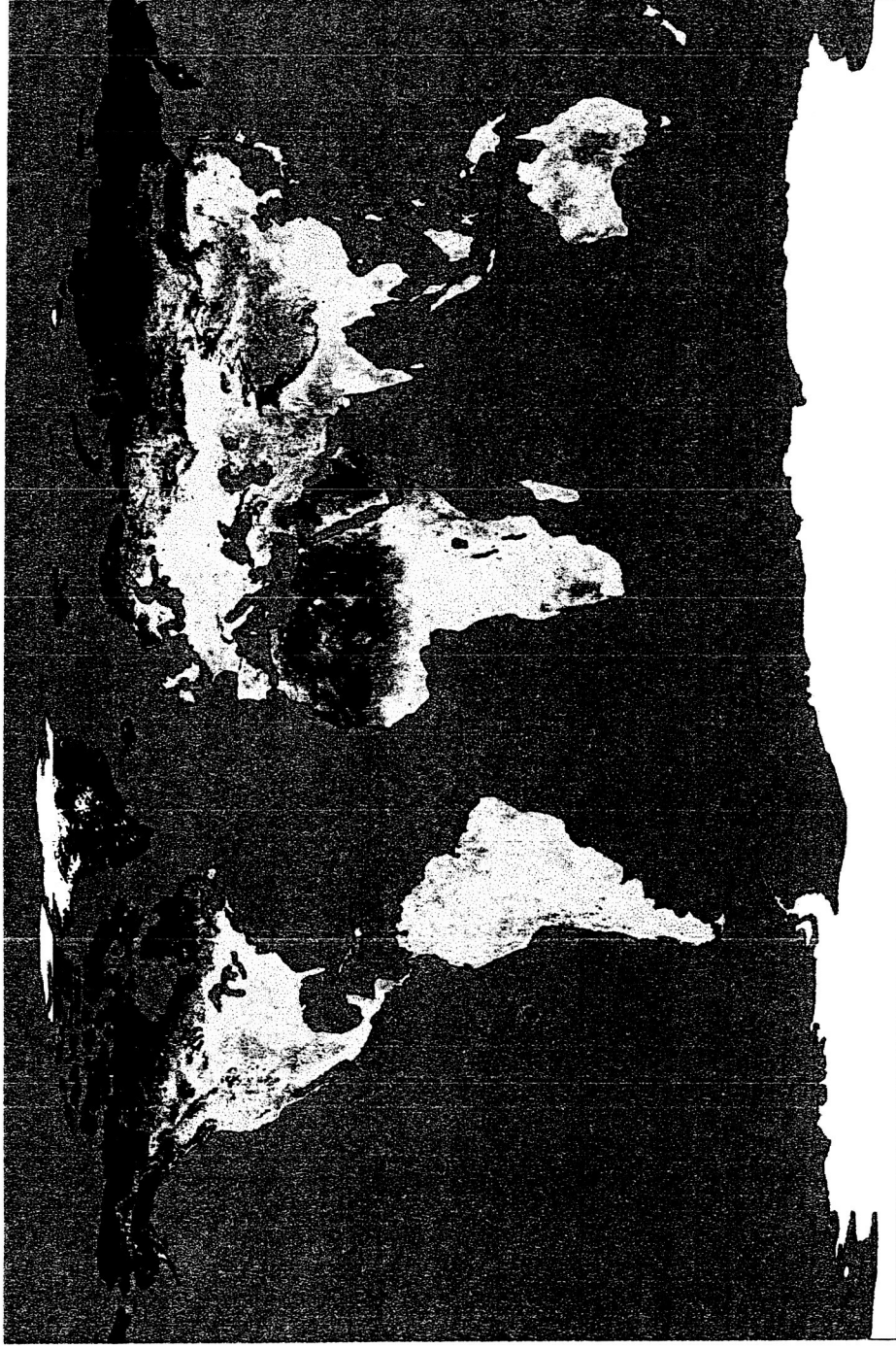


Fig. 5-The colors in this image emphasize the albedos ranging from 0.0 to 0.4 over the Earth's land surfaces. Areas colored red show the brightest, most reflective regions; yellows and greens are intermediate values; and blues and violets show relatively dark surfaces. White indicates no data were available, and no albedo data are provided over the oceans. This image was produced using data composited over a 16-day period, from April 7-22, 2002. (Image courtesy Crystal Schaaf, Boston University via NASA'S Earth Observatory)



Fig. 6-Terra views smoke plumes from fires, cirrus clouds, and lower level clouds over Siberia. (Image courtesy of NASA's Earth Observatory)

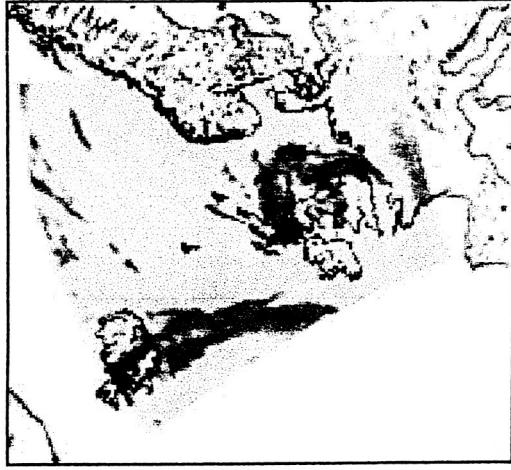


Fig. 7a-The image is from an infrared channel from the AQUA/AIRS instrument that measures the surface temperature in clear areas and cloud top temperature in cloudy areas. The image reveals very warm conditions in France and a storm of the east coast to the United Kingdom.

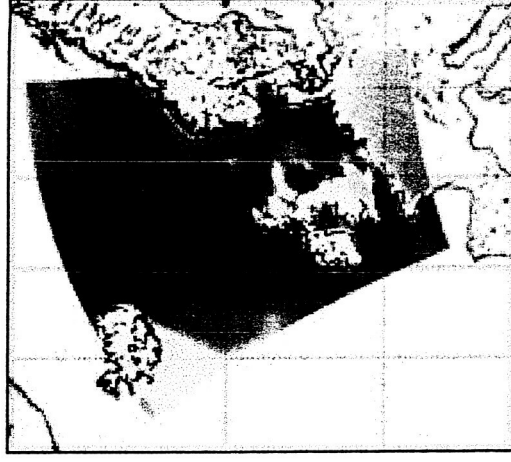


Fig. 7b.-This image represents a microwave channel from the AQUA/Advanced Microwave Sounding Unit instrument that sees through most clouds and observes surface conditions everywhere.

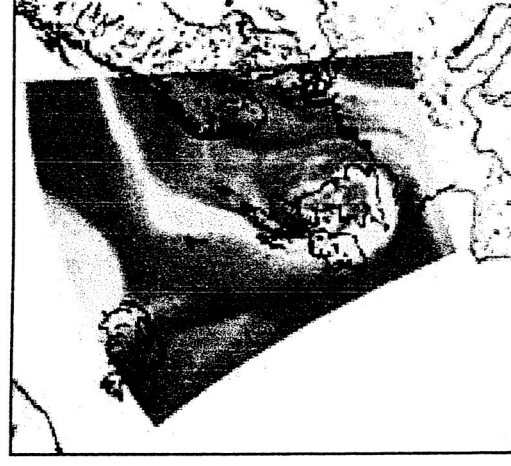


Fig. 7c-This image is a microwave channel from the Humidity Sounder for Brazil instrument that is very sensitive to humidity and does not see the surface at all, but instead reveals the structure of moisture streams in the troposphere.

Images are courtesy of NASA/GSFC Public Affairs Office.

Tropical Rainfall Measuring Mission

"Hurricane Bonnie 08/22/98"



NASA Scientific Visualization Studio (Shirah)

Fig 8-TRMM "Cat-Scan" view of a towering thunderstorm or "convective burst" in the eyewall of Hurricane Bonnie. Scientist hypothesize that such convective bursts may be a good indicator of intensification in hurricanes. Red colors represent heaviest rainfall rates. The image is produced using the unique active and passive microwave instruments aboard the TRMM observatory (Image courtesy of NASA Scientific Visualization Studio).

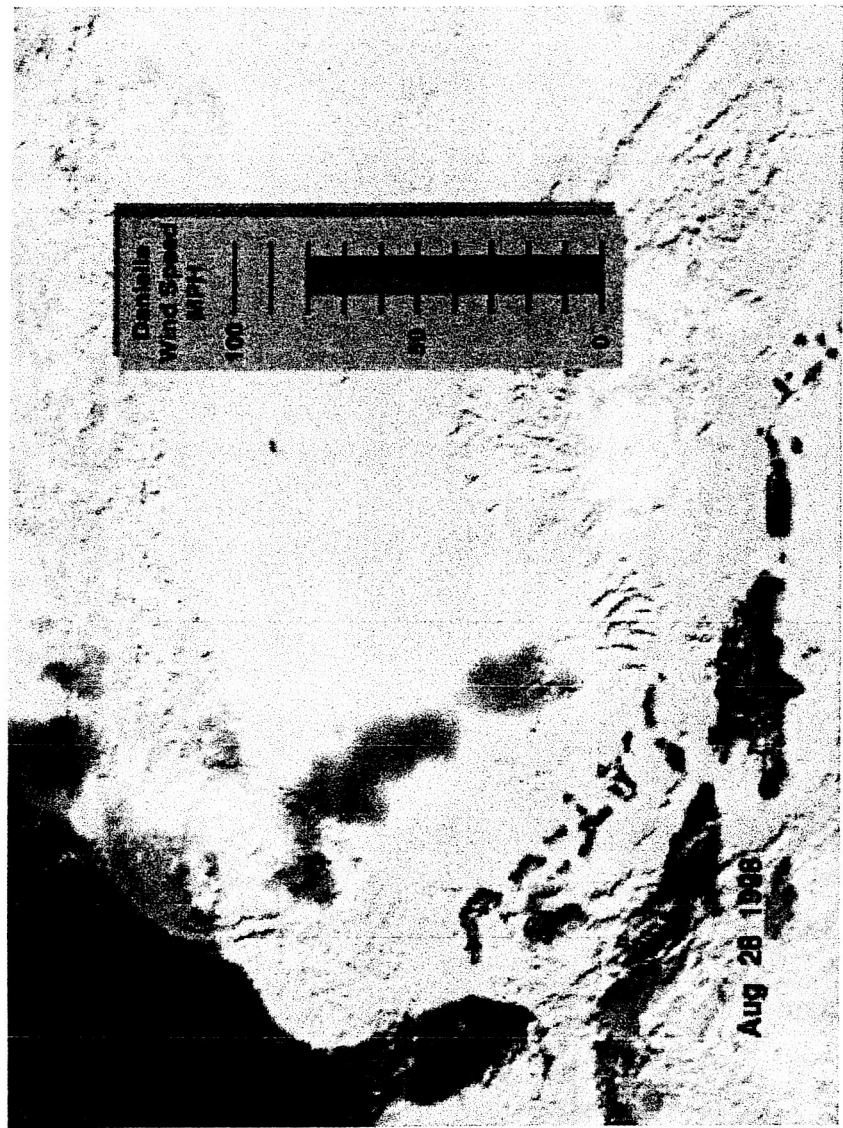


Fig. 9-High-resolution SST measurements from TRMM Microwave Imager illustrated the weakening effect of Hurricane Bonnie's cold wake on the development of Hurricane Danielle (Image courtesy of NASA Scientific Visualization Studio).

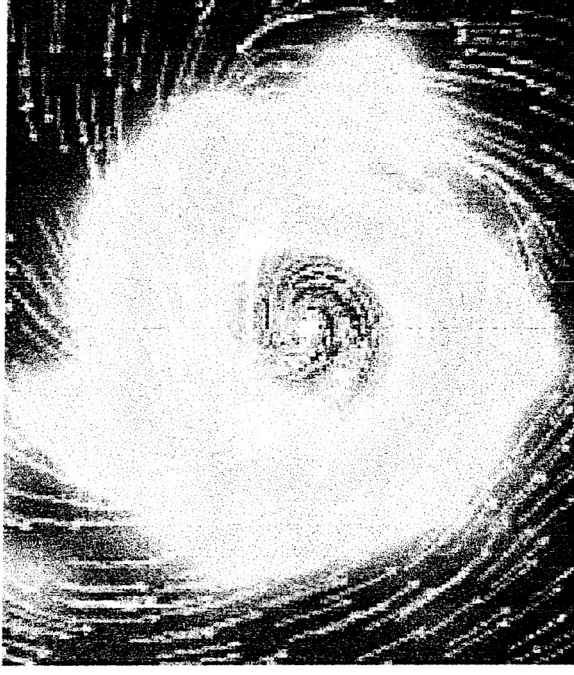


Fig. 10-The SeaWinds instrument onboard NASA's new QuikScat ocean-viewing satellite captured this image of Hurricane Dora in the eastern tropical Pacific Ocean, as it was blowing at speeds of nearly 40 meters per second (90 miles per hour). The image shows surface wind speed (colored background) and wind direction (arrows) in the vicinity of the hurricane, which was centered near 14.5 degrees north latitude and 117.8 degrees west longitude. (Image courtesy of QuikScat website, NASA's Jet Propulsion Laboratory)

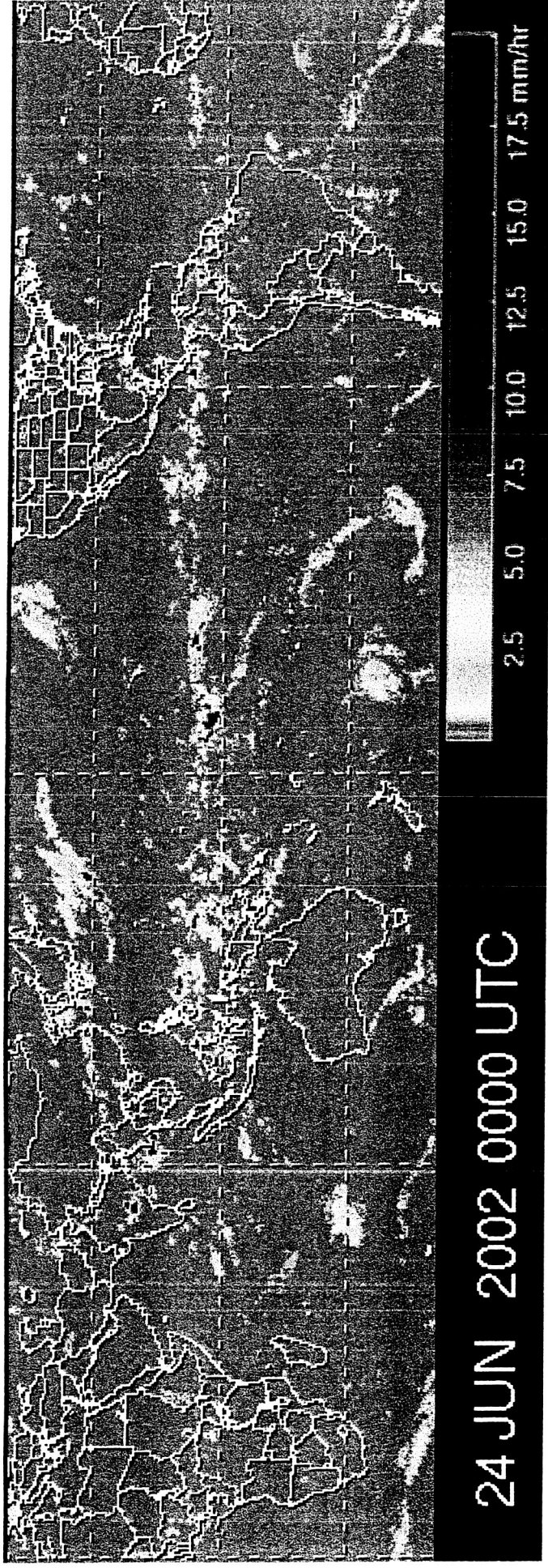


Fig. 11-Multi-Satellite Precipitation Estimates (3-hr interval)for June 24th, 2002. These estimates combine TRMM rainfall estimates with information from global rain gauges, GOES, and Special Sensor Microwave Imager aboard Defense Department weather satellites. The rainfall along the equator is associated with the Inter-Tropical Convergence Zone. Other features related to fronts and other weather systems are also evident. (Image courtesy of TRMM website, NASA)

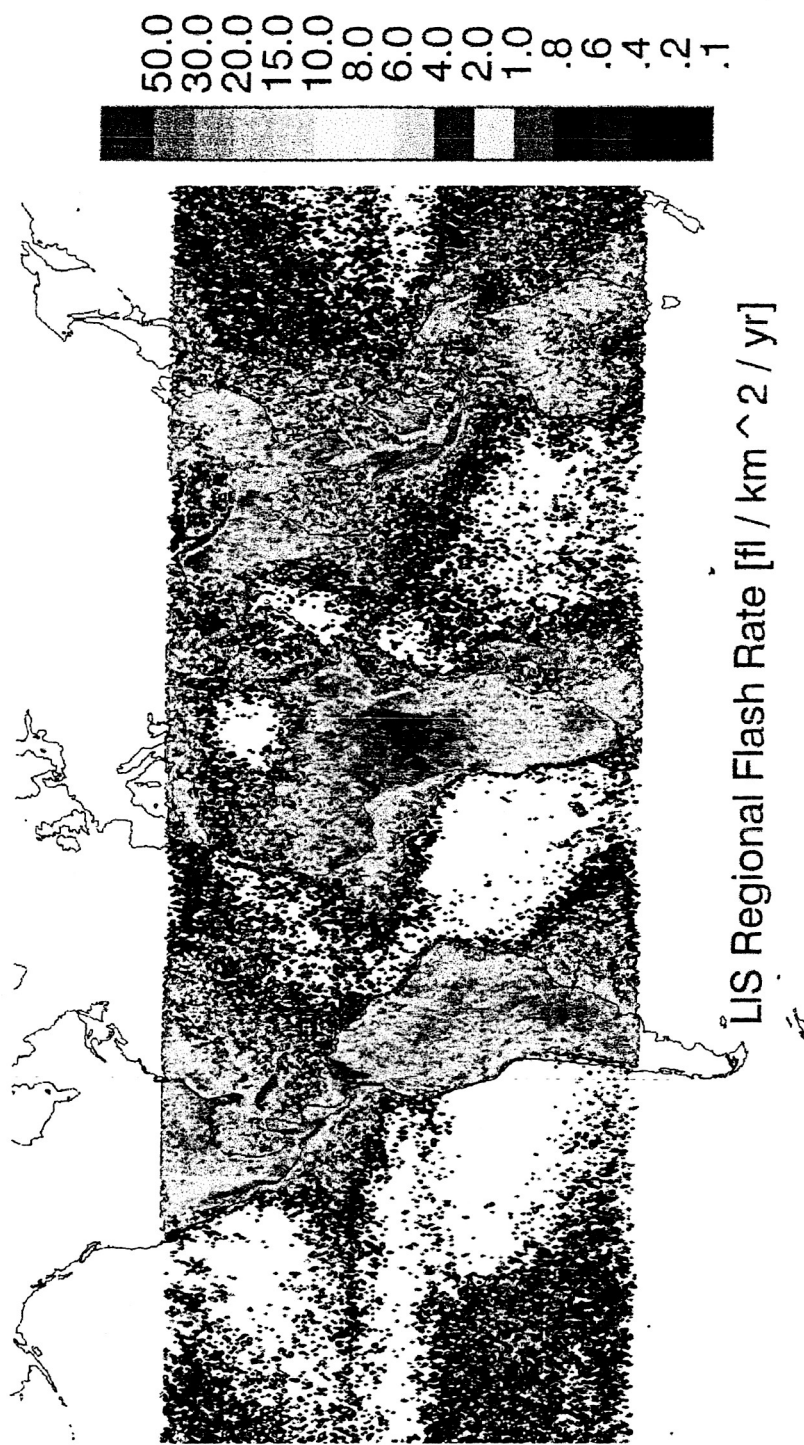
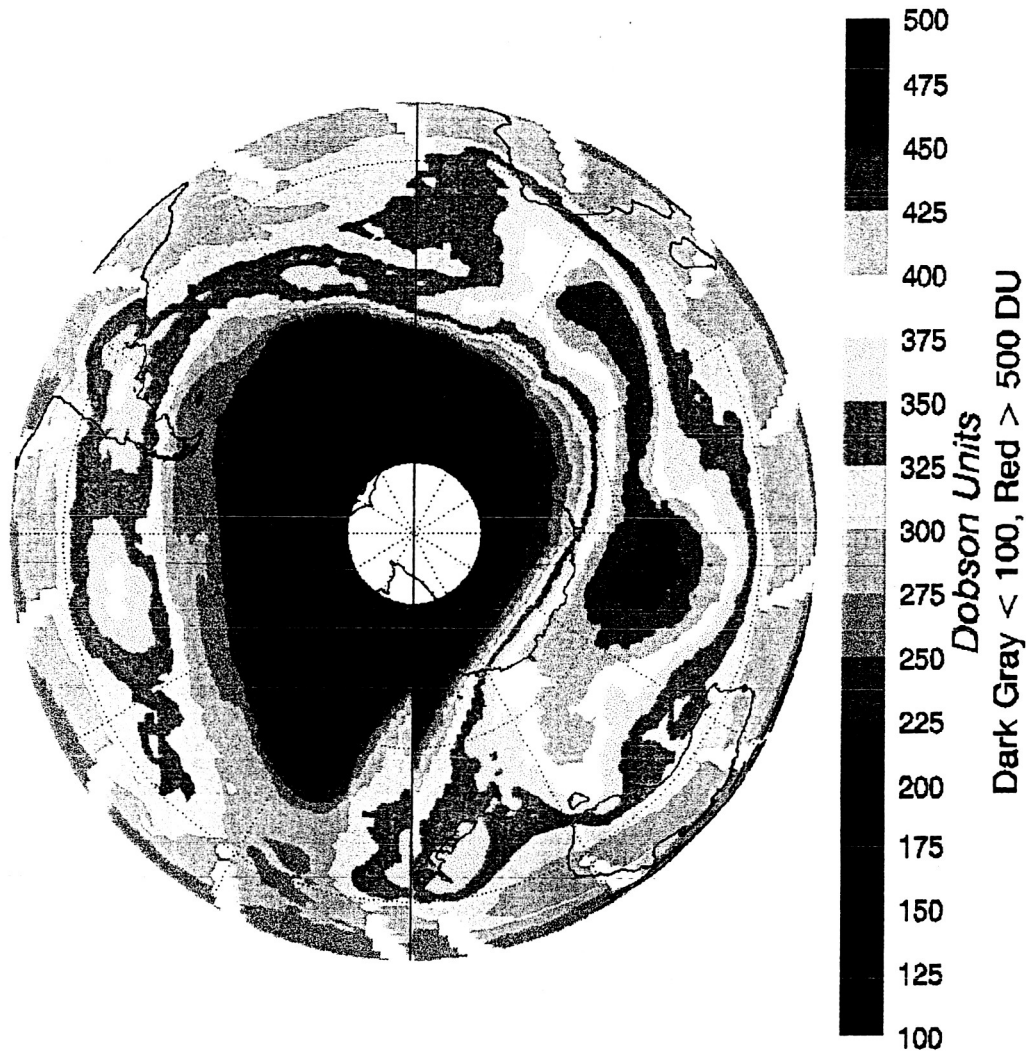


Fig. 12-Roughly three-year (1998-2000) climatology of lightning flash rates in the tropics and sub-tropic. This data was collected by the Lightning Imaging Sensor (LIS) aboard the TRMM observatory. It is interesting to observe higher flash rates over land relative to the oceans. (Image courtesy of H. Christian, NASA/MSFC)



Fig. 13-TOPEX/Poseidon ocean surface heights illustrating the 1997-1999 El Niño-La Niña event. The white values are heights above normal, and the purple values are heights below normal. During both El Niño (La Niña) the surface swells (subsides) in response to the changing sea surface temperatures and surface wind patterns (Image courtesy of NASA/TOPEX Poseidon website).

EP/TOMS Total Ozone for Sep 14, 2000



GSFC/916



Fig. 14-Depletion of ozone over Antarctica as measured by Earth Probe TOMS in September 2000. The purple values are low ozone amounts. The white circle is incomplete data (Image courtesy of NASA TOMS website).

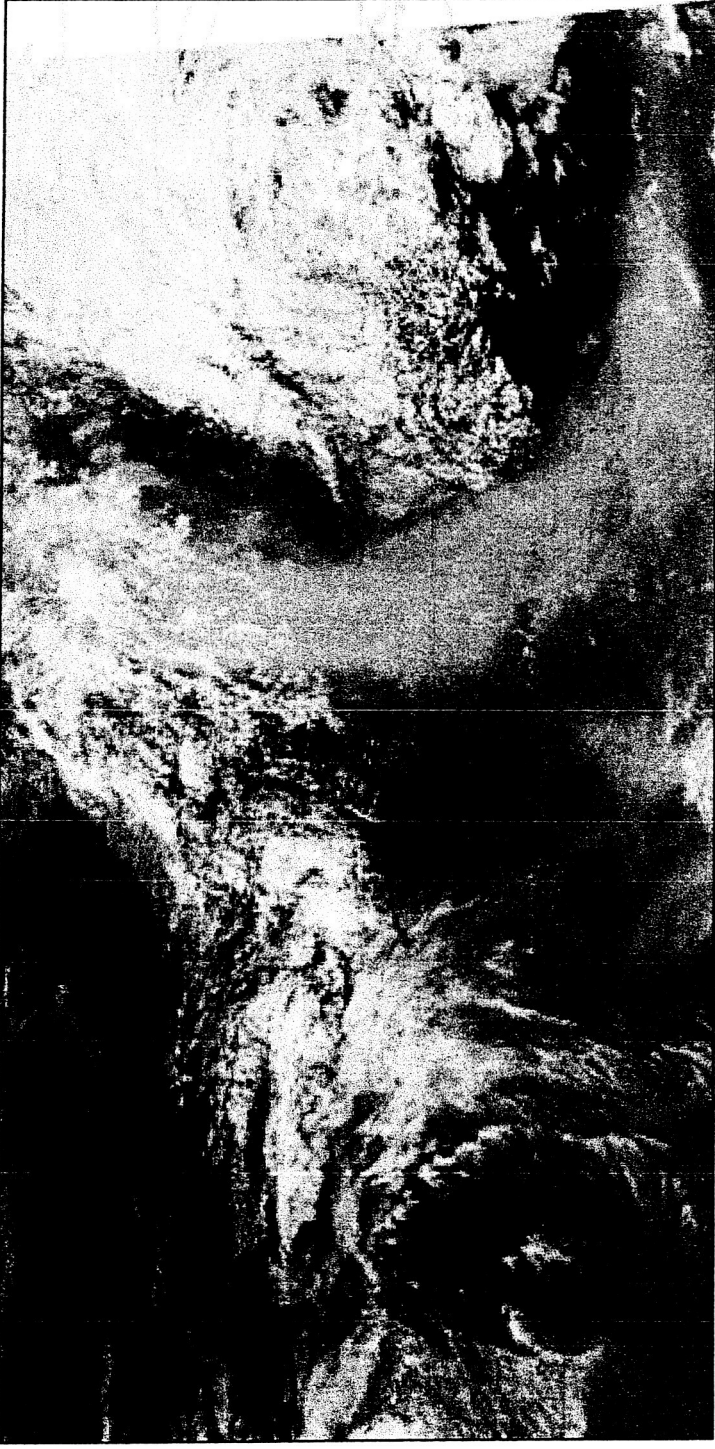


Fig. 15-Smoke from multiple large wildfires in Québec, Canada, drifted far to the south of the border, as seen in this Moderate Resolution Imaging Spectroradiometer (Aqua MODIS) image from July 7, 2002. Active fire detections are indicated with red dots. The Canadian Interagency Forest Fire Center reported there were seven out-of-control fires burning south of James Bay (the southern extension of Hudson Bay), all probably the result of lightning. (Image courtesy Jacques Descloitres, MODIS Land Rapid Response Team, NASA/GSFC)

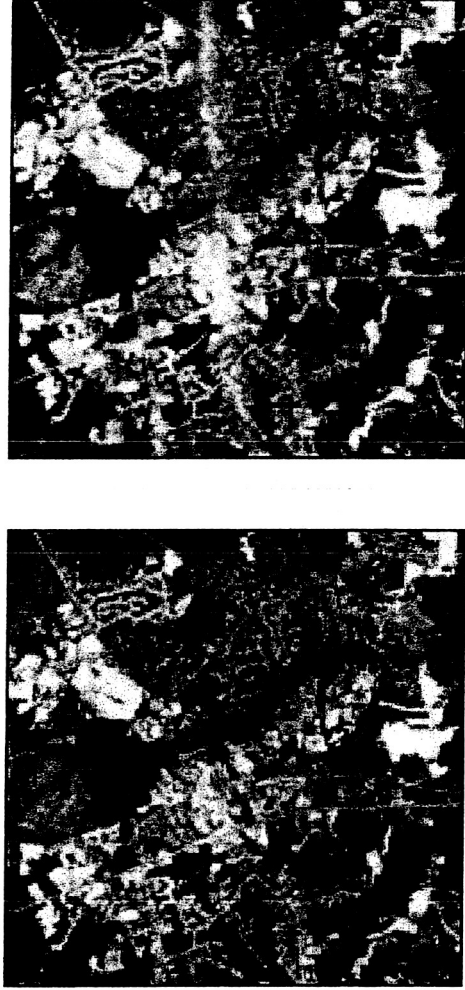
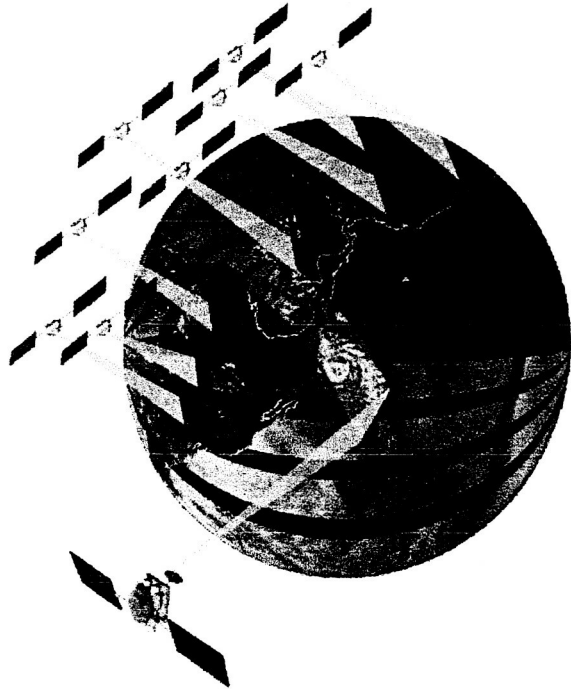
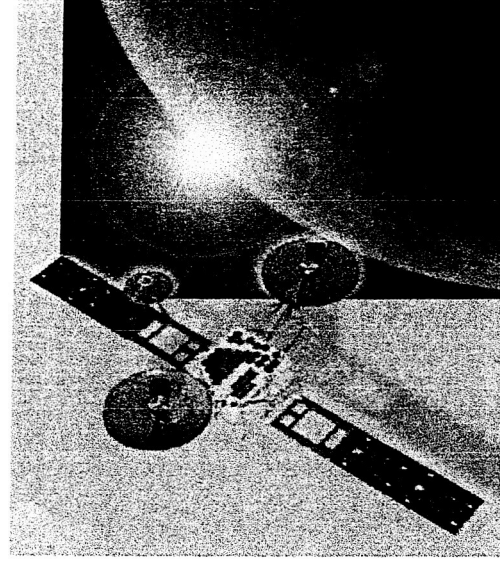


Fig. 16-A view of La Plata, Maryland before and after the passage of destructive tornadoes in the spring of 2002 as viewed from NASA's Earth Observer-1. The path of the tornado is clearly evident in the after image (Image courtesy of NASA's Earth Observatory).

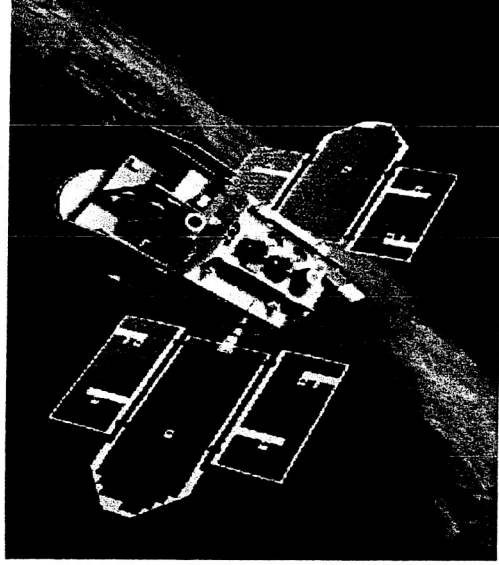
Fig. 17-Future research satellite missions addressing weather and climate issues include Global Precipitation Measurement (GPM), ICESat, Cloudsat, and EO-3-GIFTS.



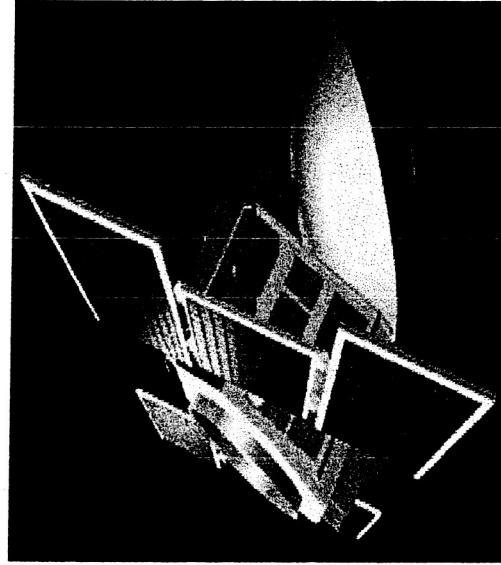
GPM



EO-3 (with GIFTS)

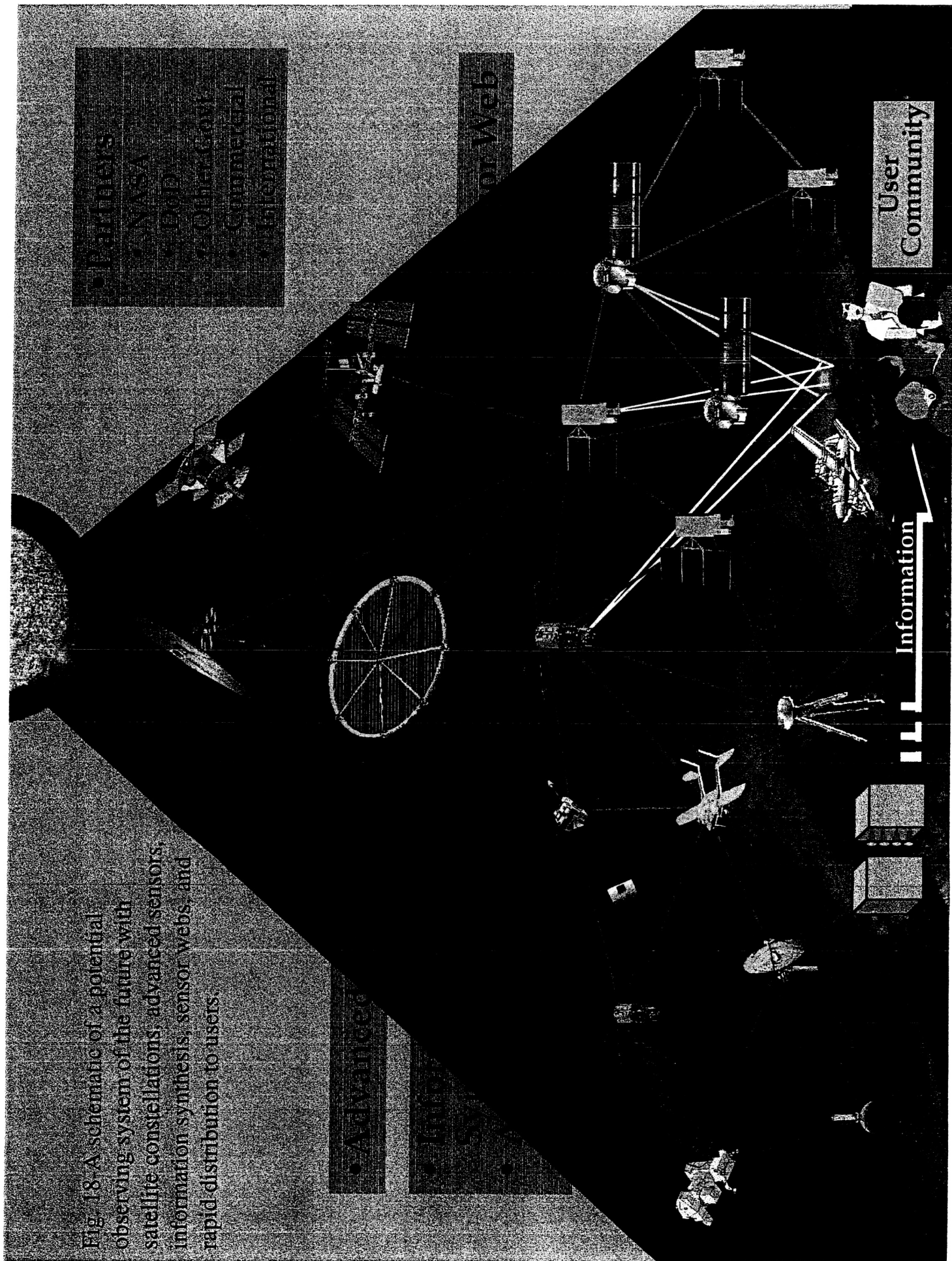


ICESat



Cloudsat

Fig. 18. A schematic of a potential observing system of the future with satellite constellations, advanced sensors, information synthesis, sensor webs, and rapid distribution to users.



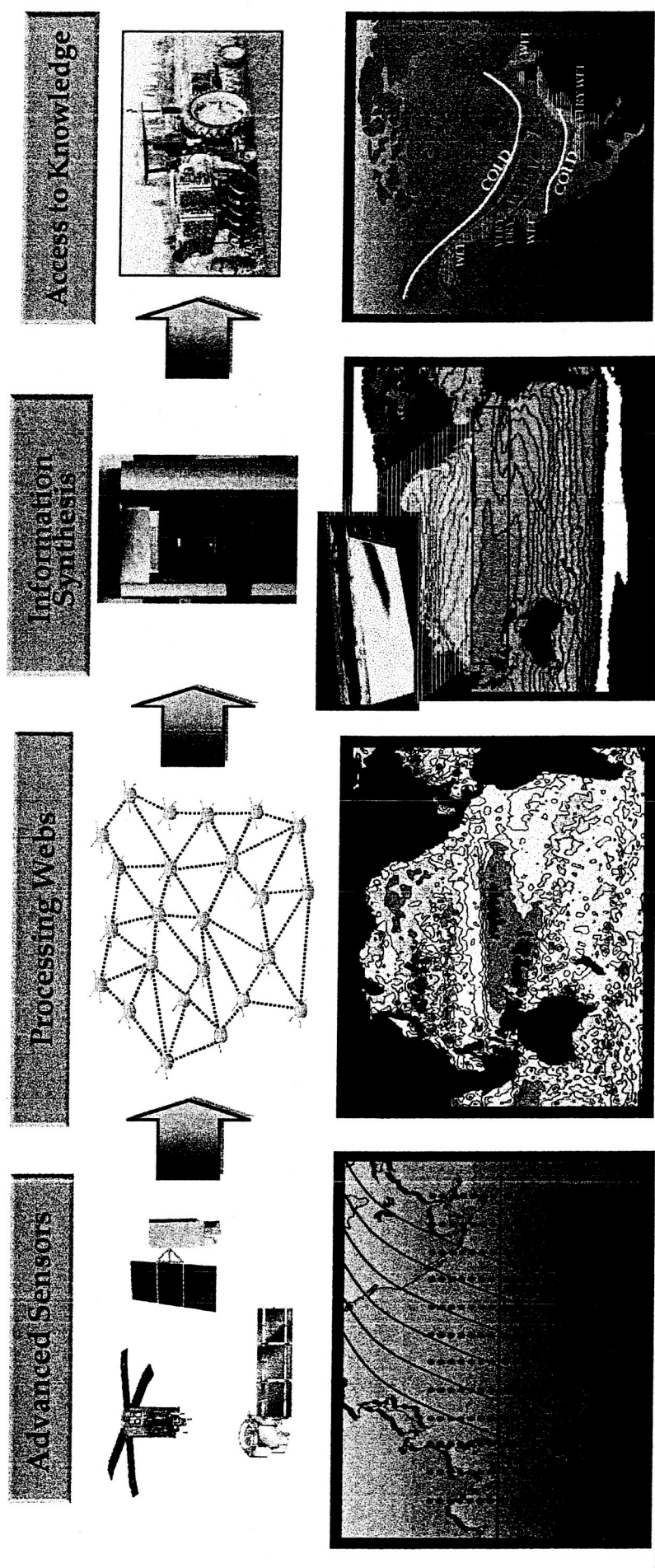


Figure 19: Roadmap from advanced sensors and processing to access to applications